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Exploitation scale of hydropower based on instream flow requirements: A case from southwest China

Yiping Fang *, Mingjie Wang, Wei Deng, Keyan Xu

Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu 610041, China

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ABSTRACT

The maximum exploitation scale and rate of hydropower is the important scientific issue to which the researchers and policy-makers always pay close attention. In this paper, on basis of various assurance levels for instream flow and in accordance with the internal relation between installed capacity of the hydropower and discharge (flow), the calculation method for the maximum exploitation scale and rate of hydropower is discussed and the empirical test was conducted by southwest China case, the results show that: (1) The calculation of exploitation scale and rate of hydropower according to instream flow as well as the equilibrium point between installed capacity of the hydropower and discharge is a effective attempt and new approach. (2) In southwest China, at the same assurance level for instream flow, the hydropower exploitation scale and rate significantly vary in major rivers. Generally, the exploitation scale is large for the river with large theoretical potentials while small for the river with small theoretical potentials; as for the exploitation rate, basically the rule is opposite. (3) The river with the maximum hydropower exploitation rate is high generally lies in the industrialized, urbanized, and densely populated regions where the sensitivity of river ecosystem is relatively low; the river with low hydropower exploitation rate generally lies in eco-sensitive areas which has a high requirement on assurance level for instream flow. (4) The maximum, moderate and excellent exploitation rates of hydropower are 16%, 12% and 8% (based on theoretical potentials); 22%, 17% and 11% (based on technologically exploitable hydropower potentials); and 34%, 25% and 17% (based on economically exploitable hydropower potentials) respectively in southwest China.

Contents

* Corresponding author. Tel.: +86 28 85229236; fax: +86 28 85222258.
E-mail addresses: ypfang@imde.ac.cn, ypfang2004@yahoo.ca (Y. Fang).

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1. Introduction

1.1. Impact of hydropower exploitation on ecosystem of rivers

Within the global range, high precipitation and steep slope are perfect pre-conditions for hydropower generation. It is also a free domestic energy production that reduces CO_2 releases in the atmosphere, a very important economic factor at regional scale, and even an important strategic approach to restructure the national energy sources [1–4]. In future, hydropower will remain as a main energy form in a relatively long term [5]. However, rivers are a complex system, and their form and behavior reflect interacting among topographical, hydrological and ecological processes [6]. The increasingly growing exploitation rate of hydropower overwhelmingly changes the discharge and water temperature of rivers, greatly disturbs the matter and energy balance of rivers, and consequently changes the natural succession direction of rivers, traditional hydropower production schemes have severe impacts on freshwater ecosystems and related benefits and goods [2]. Such a negative effect not only involves many ecological and environmental problems but also involves many challenges arising in the social and economic respects [2,5,7,8].

Accompanied with the stress of hydropower exploitation on river ecosystem, relieving stress on river ecosystem, restoring original features of rivers, and ensuring security of river ecosystem have become important actions for maintenance of health of river ecosystem taken by countries all over the world, for all this, the river restoration science focus on the relation between hydropower production and instream flow as well as the influence of hydropower generation [2]. Assessment of impact of changed flow regime on river bed and river bank ecology and provision of instream flows have become necessary in exploitation of hydropower projects [8,9–15].

1.2. Literature review of instream flow study

Various factors determine the health of a river ecosystem. These including discharge (flow), the physical structure of the channel and riparian zone, water quality, channel management. The flow has been given various names, including the environmental flow (regime), instream flow, environmental allocation, or ecological flow requirement [16]. The instream flow was focused on the concept of a minimum flow level; minimum flow is a general term used to describe a flow required to maintain some feature of a river ecosystem [15]. The concept of minimum flow originated as a stream flow standard to limit the abstraction of water during the dry season; Based on the idea that all river health problems are associated with low flows and that as long as the flow is kept at or above a critical level, the river ecosystem will be conserved [16]. Failure to maintain such flows may lead to decline in the health of water dependent ecosystem [15].

Since the mid-1970s, methods have been developed to define just what the instream flow foe a given river should be [16]. Each method has advantages and disadvantages which make it suitable for a particular set of circumstances [16]. Literature study shows that the instream flows have been generally specified in terms of discharge, no simple figure can be given for the instream flow requirement of a river (Table 1). It is related to a number of factors such as hydrological and biotic character of critical reaches, perceived sensitivity, the desired state of the river and uses to which river flow is put [15]. However, as a whole, literature review indicates that the scope of the instream flow is generally between 10% and 60%, with a consensus of three levels (10%, 30%, 60%) (see Table 1); on the other hand, the targets and key concerns of studies, according to documents of relative studies, mainly focus on the measurement, catchment abstraction management strategy (CAMS), scope and scale of instream flow. But these present the perspectives cannot broadly serve the scientific decision-making of hydropower exploitation rate or threshold. Individually, they have value but do not provide a critical basis for governments or departments of river basin management to develop hydropower resource of rivers. This paper focuses on applying flow knowledge to determine the scale of hydropower exploitation, and proposes a framework to quantify the maximum scale and rate of hydropower exploitation based on instream flow requirements.

1.3. Study methods

1.3.1. Setting assurance levels for instream flow

Referring to the progress on instream flow study in domestic and overseas (Table 1), set three assurance levels for instream flow, that is, 10% (minimum flow), 30% (moderate flow), and 60% (excellent flow).

1.3.2. Defining the balance point between installed capacity and discharge

According to the installed capacity of the setup hydropower stations in different levels and their corresponding average discharge, make statistical analysis, establish a relationship model between the installation capacity (IC) and the mean discharge (MR), and find the balance point between them (IC_0, MR_0).

1.3.3. Calculation of the maximum scale and rate of the hydropower exploitation

(1) Calculation of the exploitation scale: according to the balance point between the installed capacity and the average discharge, and the multi-annual mean runoff of estuary hydrologic stations at major rivers (MR_n), and the assurance level of instream flow α_i, calculation of the maximum installed capacity of hydropower exploitation (IC_m) under different security conditions of instream flow.

$$IC_m = \frac{(1-\alpha_i) \times MR_n}{MR_0} \times IC_0$$

(2) Calculation of exploitation rate: determining the maximum rate of hydropower exploitation (%) by the ratio of the maximum installed capacity (IC_m) and the theoretical hydropower reserves (IC_t), i.e. IC_m/IC_t.

1.3.4. Data collection

The data of installed capacity and discharge are from 274 established hydropower stations at major rivers in southwest China.

The data of multi-annual mean runoff are from river estuary hydrological stations at major rivers in 30 years.

1.4. Profile of hydropower resource in study area

1.4.1. Strategic status of southwest China in hydropower resource

Southwest China area covers southeast of the Tibetan Plateau, the Sichuan Basin, most part of the Yunnan-guizhou Plateau, and regionally including five provinces (autonomous region, or municipality) – Yunnan Province, Sichuan Province, Guizhou Province, Chongqing Municipality, and Tibet Autonomous Region. It covers an area of about 2,500,000 km^2, accounts for 26% of the whole country (Fig. 1).

According to the re-investigation result of the national hydropower resources issued by the National Development and Reform Commission in 2005, hydropower resources in China from

Table 1
Main calculation methods and results of instream flow based on literature review in domestic and overseas.

Country/basins	Techniques	Instream flow rates or range (instream flow/mean annual runoff)	References
United States	Montana method	Poor quality: 10% Moderate habitat: 30% Excellent habitat: 60%;	Kumar et al. [15] Acreman and Dunbar [16] IUCN [17] Hesse [18]
Britain	Q95 method	Flow which is equaled or exceeded 95% time	Kumar et al. [15] IUCN [17]
	Expert knowledge Integrated analytic method	15–35%	Acreman et al. [19] Petts [20]
India Satluj River	The Himachal Pradesh State Environment Protection and Pollution Control Board	15%	Kumar et al. [15]
India Bhadra River	Tenant method	Poor flow: 10% Moderate flow: 30% Excellent flow: 60%	Lenin Babu and Harish Kumara [21] Tennant [9]
Zimbabwe	Desktop hydrological method	The north-middle Zimbabwe 30–60% The dry parts of country 20–30%	Mazvimavi et al. [22]
South Africa	7-Step process approach relying on value assessments	Average range: 10–53% Moderate flow: 47%	King and Brown [23] King [24]
Yangtze River	Integrated analytic method Integrated analytic method	26.3–34.8% 22–34%	Chen and Huang [25] Wang [26]
Middle and Lower Reaches of Yangtze River	Tenant method	Minimum flow: 13.8–16.7% Moderate flow: 65.7–73.6%	Guo and Xia [27]
Baisha River Basin of Yangtze River	Integrated analytic method Tenant method	26.3%	Mu et al. [28]
Jialing River	Q90 method Tennant method Wet perimeter method	10–20% 30% 22–55%	Chang and Zhang [29]
Upper Reach of Han River	Q90 method Tenant method Wet perimeter method	10–20% 30% 29–40%	Chang et al. [30]
Han River	Improved wet perimeter method	Minimum flow: 11.08–12.55%	Shi and Huang [31]
Xiangxi River of Three Gorges Reservoir Region	Hydrological method Weighted usable area method;	10–42.9%	Li et al. [32]
Yellow River	Base flow index Upper-lower section control method	8.3–33.4% 39–61%	Yang et al. [33] Zhang et al. [34]
Lower Reach of Yellow River	Minimum flux method based on river geomorphology	Minimum flow: 7.4–8.9%	Tang et al. [35]
Haihe River	Montana method Integrated analytic method	35–74%	Xia et al. [36]
	Hydrological, biological and hydraulic methods	Minimum flow: 16.5% Moderate flow: 23.1% Excellent flow: 32.2%	Sun and Yang [37]
	Eco-runoff of high frequency	Minimum flow: 12% Moderate flow: 25% Excellent flow: 40%	Jiang et al. [38]
	Minimum flux method based on river geomorphology	Minimum flow: 5.6–12.1%	Zheng et al. [39]
Huaihe River	Monthly guarantee rate method	17.9–82.2%	Dong et al. [40]
Pearl River	Tenant method 7Q10 method Wet perimeter method	20.57–38.26%	He et al. [41]
Liaohe River	Minimum flux method based on river geomorphology	Minimum flow: 5–17%	Su et al. [42]
Songhua River	Fish habitat method Fish biomass method	Moderate flow: 19–37%	Chen et al. [43]

rivers was estimated as 694 GW (gigawatts) in theory, accounting for 16.7% of the world total, the annual theoretical generating capacity is 6080 TWh (terawatt hour); technically exploitable installed capacity is 542 GW, technically exploitable annual generating capacity is 2470 TWh; economically exploitable installed capacity is 402 GW, economically exploitable annual generally capacity is 1750 TWh [44]. However, in China, per capita hydropower resource accounted for only 55.1% of the world's average level [45].

With a massive land, greatly varied topography, and largely different precipitation, China has an unbalanced distribution of hydropower resources, generally, showing abundant in west and scarce in east, and hydropower resources in the western area are mainly in southwest. According to the technically potential, the reserves of hydropower resources in the five provinces (autonomous region or municipality) account for 66.70% of the national total, in about 360 GW; according to the economically exploitable potential, the reserves of hydropower resources in southwest

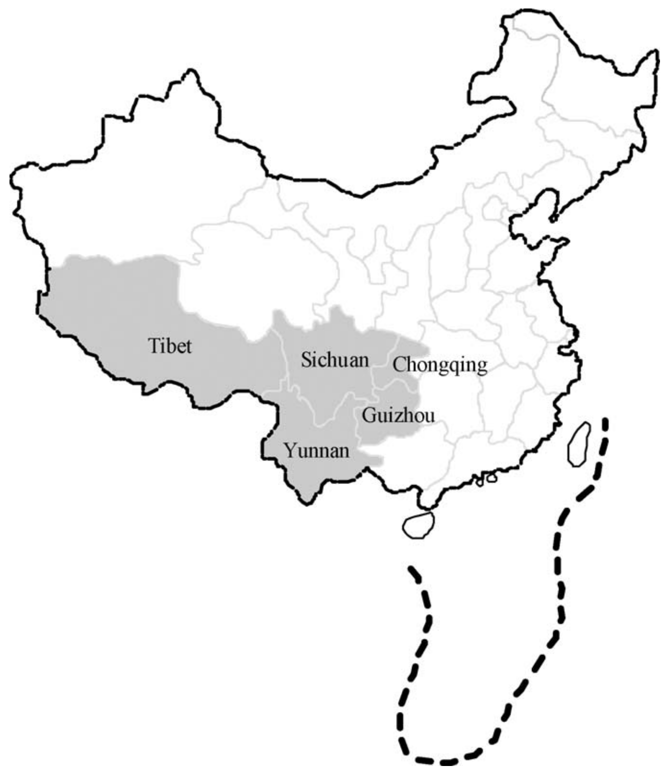


Fig. 1. The geographical position of southwest China.

account for 59.70% of the national total, in about 240 GW. The economically exploitable capacity to be developed just in Yunnan Province and Sichuan Province accounts for 63% of the national total, in about 170 GW [46]. Hydropower resources are mainly distributed in Jinsha River, Yalong River, Dadu River, Lancang River, Minjiang River, Wujiang River, main stream at upper reaches of Yangtze River, and Nujiang River [44] (Fig. 2), and hydropower resources in Yunnan Province and Sichuan Province are mainly distributed in Dadu River, Yalong River, Jinsha River, Lancang River, and Nujiang River.

1.4.2. Current situation of hydropower exploitation in southwest China

From the prospect of the energy strategies in China, hydropower generation is the sole, irreplaceable form for China to transit from highly polluted fossil fuels to clean, renewable energy, although thermal power will be still the main generation in the foreseeable future. Hydropower generation plays a decisive role in China's energy structure [47]. Since China made the guideline of giving priority to hydropower exploitation in the 21st century, hydropower development in China brought an unprecedented opportunity [48]. By the end of 2007, the hydropower installed capacity of China has reached up to 148 GW, making up 20.64% of the electric installed gross capacity. According to the technically potential, the hydropower exploitation rate reaches 27.35%. The hydropower installed capacity of the five provinces (autonomous region or municipality) in southwest reaches 42.29 GW, accounting for 48.45% of the electric installed gross capacity in southwest. The average exploitation rate of hydropower resource in southwest China is 18.20%, and among them, Guizhou Province reaches 63.56%, Sichuan Province and Chongqing Municipality 24.11%, Yunnan Province 16.27%, and Tibet Autonomous Region only 0.71% [49].

2. Result and discussion

2.1. Relationship model between installed capacity and discharge

Based on the installed capacity of the 274 power stations at major rivers in the southwest China and the discharge data of the corresponding power stations, building fitting models by statistical analysis (Figs. 3–7):

For Yunnan Province:

$$MR_1 = -0.0023(IC_1)^2 + 6.3132(IC_1) + 70.038;$$

For Sichuan Province (including Chongqing Municipality):

$$MR_2 = -0.0019(IC_2)^2 + 5.7596(IC_2) + 231.70;$$

For Guizhou Province:

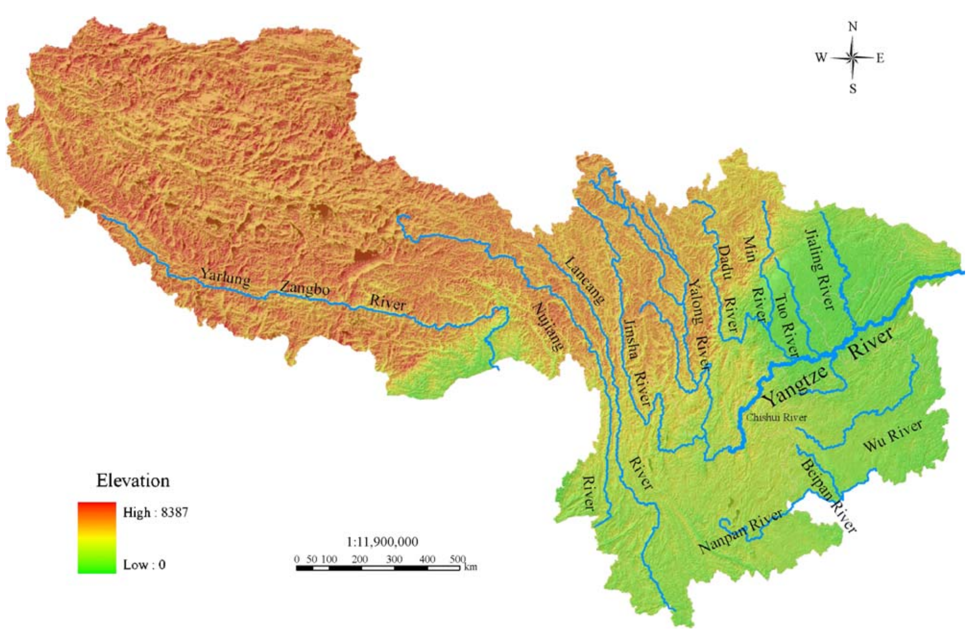


Fig. 2. The topography and main rivers of southwest China.

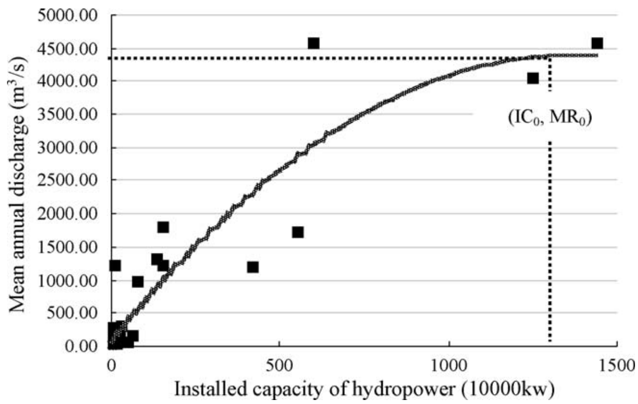


Fig. 3. The fitting curve between installed capacity and discharge in Yunnan Province.

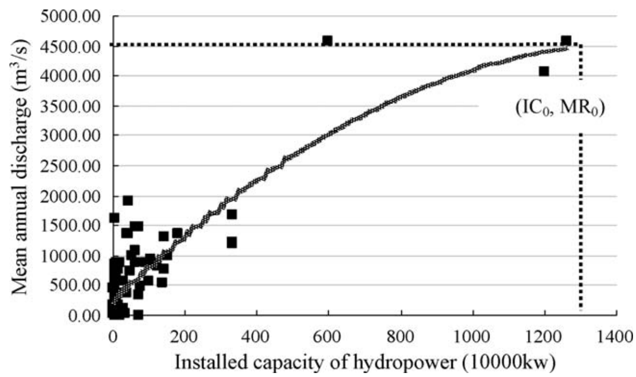


Fig. 4. The fitting curve between installed capacity r and discharge in Sichuan Province (including Chingqing Municipality).

$$MR_3 = -0.017(IC_3)^2 + 6.5533(IC_3) + 81.354;$$

For Tibet Autonomous Region:

$$MR_4 = -0.2475(IC_4)^2 + 23.967(IC_4) + 35.741;$$

For the southwest China:

$$MR_5 = -0.0021(IC_5)^2 + 6.0075(IC_5) + 146.53;$$

Where IC_i is the installed capacity of a hydropower station; MR_i is the mean annual discharge of corresponding hydropower station, and i (i = 1,2,3,4,5) is code number of provinces or regions, namely 1 stand for Yunnan Province, 2 stand for Sichuan province(including Chongqing Municipality), 3 is Guizhou Province, 4 is Tibet Autonomous Region, and 5 is the southwest China.

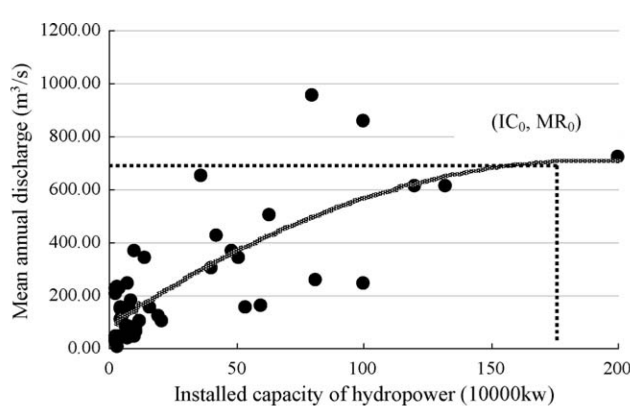


Fig. 5. The fitting curve between installed capacity and discharge in Guizhou Province.

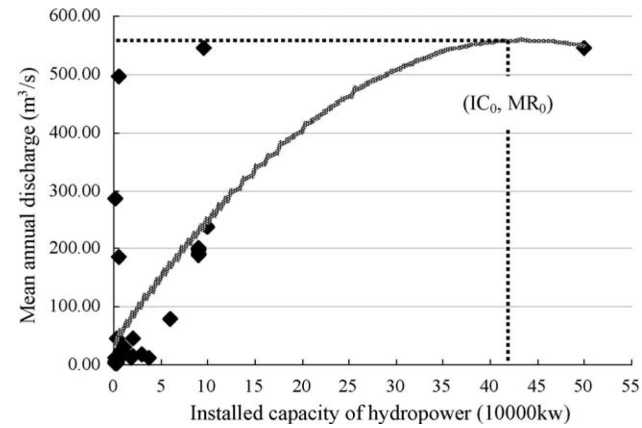


Fig. 6. The fitting curve between installed capacity r and discharge in Tibet Autonomous Region.

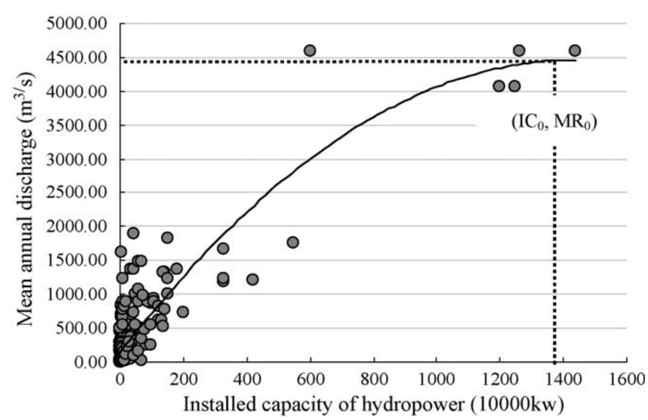


Fig. 7. The fitting curve between installed capacity and discharge in southwest China.

2.2. Statistical test for fitting models

According to the fitting models, statistical testing with SPSS tool (Table 2):

Goodness of fit test (R^2 test): when a plot is made, and the coefficient of determination, R^2, of the fitting models is computed, the model can be tested based on this value. Results show except that R^2 of Tibet Autonomous Region and Guizhou Province is slightly lower, others are above 0.7. However, the correlation coefficients (R) in the fitting models are above 0.678, showing that the goodness of fit of the fitting models is good; so it can be used to analyze the relationship between installed capacity and discharge.

Level of significance test (F-test): an F-test is any statistical test in which the test statistic has an F-distribution under the null hypothesis. It is most often used when comparing statistical models that have been fit to a data set, in order to identify the model that best fits the population from which the data were sampled. Analysis result shows that the values of probability (p-value) are all below 0.001. It means that there is a nonlinear

Table 2
The statistical test of fitting models between installed capacity and discharge in southwest China.

Regions	R-square	F value	Significance
Yunnan Province	0.8711	212.848	0.000
Sichuan Province (including Chongqing)	0.7205	165.523	0.000
Guizhou Province	0.5964	32.505	0.000
Tibet Autonomous Region	0.4593	12.319	0.000
Entire southwest China	0.7793	487.396	0.000

Table 3
The balance point between installed capacity of hydropower and discharge.

Regions	Regression models	Balance points (IC_0, MR_0)
Yunnan Province	$MR_1 = -0.0023\ (IC_1)^2 + 6.3132\ (IC_1) + 70.038$	(1372.44, 4402.27)
Sichuan Province (including Chongqing)	$MR_2 = -0.0019\ (IC_2)^2 + 5.7596\ (IC_2) + 231.70$	(1515.68, 4596.57)
Guizhou Province	$MR_3 = -0.017\ (IC_3)^2 + 6.5533\ (IC_3) + 81.354$	(192.74, 712.91)
Tibet Autonomous Region	$MR_4 = -0.2475\ (IC_4)^2 + 23.967\ (IC_4) + 35.741$	(43.66, 558.89)
Entire southwest China	$MR_5 = -0.0021\ (IC_5)^2 + 6.0075\ (IC_5) + 146.53$	(1430.36, 4430.94)

relationship between the independent variable (*IC*) and the dependent variable (*MR*), and the fitting models are meaningful.

2.3. Equilibrium point between installed capacity and discharge

According to fitting function $MR = f(IC)$, because $MR = f(IC)$ satisfies:

(1) it is meaningful at point IC_0;
(2) the left hand limit $\lim_{\nabla ic \to 0^-} (\Delta MR/\Delta IC)$ and right hand limit $\lim_{\nabla ic \to 0^+} (\Delta MR/\Delta IC)$ exist; and
(3) both left and right hand limit is equal, namely $\lim_{\nabla ic \to 0^-} (\Delta MR/\Delta IC) = \lim_{\nabla ic \to 0^+} (\Delta MR/\Delta IC)$.

Therefore, the fitting function is derivable. According to the definition of derivative, the slope of a function is called the derivative. If the first derivative is zero ($\mathrm{d}MR/\mathrm{d}IC = \lim_{\Delta IC \to 0}(\Delta MR/\Delta IC) = 0$), it means that the slope is zero, namely, showing that the discharge (*MR*) (dependent variable) does not change with the installed capacity (*IC*) (independent variable). Here, the corresponding point (IC_0, MR_0) of first derivative is zero is called the balance point between installed capacity and discharge (Table 3).

Table 4
The scale and rate of hydropower exploitation under different instream flow conditions based on theoretical potentials in major rivers of southwest China.

	Estimated by provinces			Estimated by entire southwest China			Mean		
	10%	30%	60%	10%	30%	60%	Maximum exploitation level	Moderate exploitation level	Excellent exploitation level
Jinsha River									
Exploitation scale (10000 kw)	1462.6	1138.3	651.9	1429.5	1111.8	635.3	**1446.0**	**1125.1**	**645.3**
Exploitation rate (%)	44.2	34.4	19.7	43.2	33.6	19.2	**43.7**	**34.0**	**19.5**
Yalong River									
Exploitation scale (10000 kW)	566.5	441.7	252.9	556.4	431.6	242.8	**563.1**	**438.4**	**249.5**
Exploitation rate (%)	16.8	13.1	7.5	16.5	12.8	7.3	**16.7**	**13.0**	**7.4**
Dadu River									
Exploitation scale (10000 kW)	623.1	485.0	276.2	613.0	474.9	272.8	**619.7**	**481.6**	**276.2**
Exploitation rate (%)	18.5	14.4	8.2	18.2	14.1	8.1	**18.4**	**14.3**	**8.2**
Min River									
Exploitation scale (10000 kW)	845.7	657.7	375.9	827.4	643.7	367.4	**837.3**	**650.7**	**371.6**
Exploitation rate (%)	60.3	46.9	26.8	59.0	45.9	26.2	**59.7**	**46.4**	**26.5**
Tuo River									
Exploitation scale (10000 kW)	135.0	105.1	59.9	132.2	102.9	58.8	**133.7**	**104.0**	**59.4**
Exploitation rate (%)	72.3	56.3	32.1	70.8	55.1	31.5	**71.6**	**55.7**	**31.8**
Jialing River									
Exploitation scale (10000 kW)	628.6	490.1	280.0	616.4	479.4	274.0	**622.5**	**485.5**	**277.0**
Exploitation rate (%)	41.3	32.2	18.4	40.5	31.5	18.0	**40.9**	**31.9**	**18.2**
Lancang River									
Exploitation scale (10000 kW)	611.1	475.8	272.9	633.6	491.6	281.9	**622.4**	**484.8**	**277.4**
Exploitation rate (%)	27.1	21.1	12.1	28.1	21.8	12.5	**27.6**	**21.5**	**12.3**
Nu River									
Exploitation scale (10000 kW)	629.8	491.5	280.3	655.3	509.7	291.3	**644.4**	**502.4**	**287.6**
Exploitation rate (%)	17.3	13.5	7.7	18.0	14.0	8.0	**17.7**	**13.8**	**7.9**
Wu River									
Exploitation scale (10000 kW)	400.4	311.7	178.3	479.6	373.3	212.7	**440.0**	**343.0**	**196.0**
Exploitation rate (%)	38.4	29.9	17.1	46.0	35.8	20.4	**42.2**	**32.9**	**18.8**
Nanpan River									
Exploitation scale (10000 kW)	127.0	98.5	56.5	151.2	118.1	67.1	**139.3**	**108.3**	**62.0**
Exploitation rate (%)	29.9	23.2	13.3	35.6	27.8	15.8	**32.8**	**25.5**	**14.6**
Beipan River									
Exploitation scale (10000 kW)	93.3	72.5	41.4	111.6	86.6	49.7	**102.6**	**79.5**	**45.5**
Exploitation rate (%)	29.1	22.6	12.9	34.8	27.0	15.5	**32.0**	**24.8**	**14.2**
Chishui River									
Exploitation scale (10000 kW)	72.0	56.0	32.0	86.0	66.9	38.2	**79.0**	**61.4**	**35.2**
Exploitation rate (%)	56.7	44.1	25.2	67.7	52.7	30.1	**62.2**	**48.4**	**27.7**
Yarlung Zangbo River									
Exploitation scale (10000 kW)	308.6	245.3	134.5	1289.6	996.9	569.6	**799.1**	**625.0**	**356.0**
Exploitation rate (%)	3.9	3.1	1.7	16.3	12.6	7.2	**10.1**	**7.9**	**4.5**

2.4. Maximum hydropower exploitation scale and rate of major rivers

The theoretical potentials of hydropower, multi-annual mean runoff parameter of estuary hydrological stations on major rivers, the balance point (value) between installed capacity and discharge are used as basis for analysis exploitation level of hydropower, it is easy to calculate the maximum exploitation scale and rate of rivers at 10% (minimum flow), 30% (moderate flow), and 60% (excellent flow) flow assurance levels (Table 4).

Table 4 illustrates that, major rivers in southwest China are in the same assurance level of instream flow, scale as well as rate of hydropower exploitation differs greatly. Clearly, rivers with larger theoretical potentials (i.e. Jinsha River, Yalong River, Dadu River, Lancang River, Nujiang River, Yarlung Zangbo River, Minjiang River, etc.) have large exploitation scales (i.e. maximum, moderate, and excellent exploitation scales), while rivers with smaller theoretical potentials (i.e. Tuojiang River, Jialing River, Nanpan River, Beipan River, Chishui River, etc.) have small exploitation scales (maximum, moderate, and excellent exploitation scales). However, the exploitation rate shows an opposite rule, that is, rivers with smaller theoretical potentials have higher exploitation rates (maximum, moderate, and excellent exploitation rates) than those with larger theoretical potentials, mainly because:

(1) In statistical 274 hydropower stations, they are mainly small-to-medium sized plants, and distribute at Wujiang River, Nanpan River, Beipan River, Tuojiang River, Jialing River, Minjiang River. Compared with super-scale and large-scale sized hydropower stations, they cut less flow at the downstream, to some extent, thus increasing the parameter item "$(1-\alpha_i)\times MR_n$" in equation $IC_m = (((1-\alpha_i)\times MR_n)/MR_0)\times IC_0$.
(2) Comparatively, Wujiang River, Nanpan River, Beipan River, Jialing River, Chishui River, Tuojiang River hold smaller theoretical potentials besides Jinsha River and Minjiang River, namely, whose IC_t value is smaller than other rivers. As parameter item $(1-\alpha_i)\times MR_n$ increases in equation $IC_m = (((1-\alpha_i)\times MR_n)/MR_0)\times IC_0$, the ratio of IC_m to IC_t increases, and the parameter value of exploitation rate increases.
(3) The river basins with higher exploitation rate (Tuojiang River, Chishui River, Minjiang River, Wujiang River, Jialing River, the middle and lower reaches of Jinsha River, Nanpan River, and Beipan River) where industrialization and urbanization are intense. Many of metropolises such as Chengdu, Chongqing, Guiyang, as well as large and medium cities such as Panzhihua, Yibin, Zigong, Neijiang, Luzhou, Nanchong, Suining, Guang'an, Zunyi are distributed in these areas.

On the other hand, the river basins with higher exploitation rate (Tuojiang River, Chishui River, Minjiang River, Wujiang River, Jialing River, the middle and lower reaches of Jinsha River, Nanpan River, and Beipan River), the river ecosystem is less sensitive than those of Yarlung Zangbo River, Yalong River, Dadu River, Nujiang River, Lancang River, and the upper reaches of Jinsha River [50]. Therefore, it is necessary to keep Yarlung Zangbo River, Yalong River, Dadu River, Nujiang River, Lancang River, and the upper reaches of Jinsha River higher assurance level of instream flow, and to reduce the exploitation rate of hydropower resources.

According to the above analysis and calculation, in entire southwest China, the maximum, moderate, and excellent exploitation rates of hydropower resources are 16%, 12%, 8% based on theoretical potentials; 22%, 17%, 11% based on technologically exploitable hydropower potentials; and 34%, 25%, 17% based on economically exploitable hydropower potentials respectively.

Reflecting on the challenges facing rapidly hydropower development, it is clear that the scientific understanding and determination of hydropower exploitation scale and rate is very necessary to maintain rivers health in China. During hydropower development, emphasis should be laid on the assessment of the minimum flow requirements and corresponding exploitable level of hydropower and the exploitation threshold of hydropower resource at different rivers should be given special attention.

3. Conclusion

(1) It is an effective attempt and new approach to calculate the security exploitation scale and rate by the instream flow requirements and the equilibrium point between hydropower installed capacity and discharge.
(2) Under the same assurance level of instream flow, the major rivers in southwest China differ greatly in exploitation scale and rate. Generally speaking, rivers with large theoretical potentials have large exploitation scale (total amount), and vice versa; while the exploitation rate shows an opposite rule.
(3) The river basins with high exploitation rate of hydropower where industrialization and urbanization are intense, but the river ecosystem is less sensitive; on the other hand, the river basins with low hydropower exploitation rate, ecosystem in these areas are frangible and sensitive, it is necessary to keep high assurance level of instream flow. Therefore, it is very important to reduce the exploitation degree of hydropower in these river basins.
(4) The maximum, moderate and excellent exploitation rates of hydropower are 16%, 12%, 8% (based on theoretical potentials); 22%, 17%, 11% (based on technological exploitable potentials); and 34%, 25%, 17% (based on economically exploitable potentials) in southwest China respectively.
(5) Reflecting on the challenges facing rapidly hydropower development, it is clear that the scientific understanding and determination of hydropower exploitation scale and rate is very necessary to maintain rivers health in China. During hydropower development, emphasis should be laid on the assessment of the minimum flow requirements and corresponding exploitable level of hydropower and the exploitation threshold of hydropower resource at different rivers should be given special attention.

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